INDIVIDUAL THYROID DOSE ESTIMATION FOR A CASE-CONTROL STUDY OF CHERNOBYL-RELATED THYROID CANCER AMONG CHILDREN OF BELARUS—PART I: ^{131}I, SHORT-LIVED RADIOIODINES (^{132}I, ^{133}I, ^{135}I), AND SHORT-LIVED RADIOTELLURIUMS (^{131M}Te AND ^{132}Te)

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Abstract—**Large amounts of radioiodines were released into the atmosphere during the accident at the Chernobyl nuclear power plant on 26 April 1986. In order to investigate whether the thyroid cancers observed among children in Belarus could have been caused by radiation exposures from the Chernobyl accident, a team of Belarusian, Russian, and American scientists conducted a case-control study to compare cases and controls according to estimated thyroid dose. The primary purpose of this paper is to present detailed information on the estimated thyroid doses, due to intakes of ^{131}I, that were used in the case-control study. The range of the ^{131}I thyroid doses among the 107 cases and the 214 controls was found to extend from 0.00002 to 4.3 Gy, with medians of approximately 0.2 Gy for the cases and 0.07 Gy for the controls. In addition, the thyroid doses resulting from the intakes of short-lived radioiodines (^{132}I, ^{133}I, and ^{135}I) and radiotelluriums (^{131m}Te and ^{132}Te) were estimated and compared to the doses from ^{131}I. The ratios of the estimated thyroid doses from the short-lived radionuclides and from ^{131}I for the cases and the controls range from 0.003 to 0.1, with median values of approximately 0.02 for both cases and controls.**
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Key words: Chernobyl; thyroid; cancer; children

INTRODUCTION

THE ACCIDENT at the nuclear power plant in Chernobyl in northwestern Ukraine on 26 April 1986 released large amounts of radioactive materials. Of particular concern were the releases of 1.3 to 1.8 exabecquerels (10^{18} Bq) of ^{131}I plus similar amounts of shorter lived radioiodines (^{132}I and ^{133}I), much of it contaminating southern areas of Belarus (IAEA 1996; UNSCEAR 2000). Anticipating an increase in thyroid cancer, Soviet health authorities initiated an intensive medical screening program among children in areas of heavy fallout (Ministry of Health 1987; Astakhova 1990). In 1992, the number of cases of thyroid cancer in children of Belarus following the accident was reported to be 131 (Kazakov et al. 1992). In order to investigate whether these thyroid cancers could have been caused by radiation exposures from the Chernobyl accident, a team of Belarusian, Russian, and American scientists decided to undertake a case-control study to compare cases and controls according to estimated ^{131}I thyroid dose. An extensive discussion of the clinical and epidemiological aspects of the study was published separately (Astakhova et al. 1998). In this paper, the estimation of the individual thyroid doses resulting from intakes of ^{131}I is discussed, and the results are presented according to area of residence at the time of the accident.

In addition, three other, usually minor, contributions to the thyroid dose have been evaluated in the framework of the study: (1) the dose from internal irradiation resulting from intakes of short-lived radioiodines (^{132}I, ^{133}I, and ^{135}I) and of short-lived radiotelluriums (^{131m}Te and ^{132}Te); (2) the dose from internal irradiation resulting from intakes of long-lived radionuclides such as ^{134}Cs and ^{137}Cs; and (3) the dose from external irradiation resulting from the deposition of radionuclides on the ground and other materials. The individual thyroid doses resulting from intakes of short-lived radioiodines and radiotelluriums are presented in this paper while the

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doses due to the other two contributions will be presented in a companion paper.[§§] It is important to take the short-lived radionuclides into consideration because of the suspicion that short-lived radionuclides are more effective for thyroid cancer induction than ^{131}I (NCRP 1985).

DATA

The subjects included in the case-control study consist of (1) a group of 107 cases, who were children at the time of the accident and who were diagnosed with thyroid cancer before 1 March 1992, and (2) a group of 214 controls, matched with the cases according to sex and year of birth, and, to some extent, location (Astakhova et al. 1998). The two groups were generated by endocrinologists and epidemiologists.

Geographical and age distribution of cases and controls

The Republic of Belarus is administratively divided into six regions (Oblasts), which are in turn divided into districts (raions). However, for the purposes of the study, the Republic of Belarus was subdivided into 10 zones that do not systematically correspond to the administrative division of the country, but are deemed to be relatively homogeneous with regard to the environmental radiation situation resulting from the Chernobyl accident. Fig. 1 shows the location of the 10 zones as well as the six regions of the country. In selecting the zones, special consideration was given to (a) the highly contaminated areas of the Central Spot (within approximately 50 km of the reactor site) and of the Gomel-Mogilev Spot (the area between the cities of Gomel and Mogilev) and (b) the rural and urban areas, which differ according to the type of milk supply. The 10 zones are (1) the Belarusian part of the 30-km evacuated area, where the relative importance of short-lived radionuclides was the greatest because of its proximity to the reactor and its contamination soon after the initial explosion; (2) the southern part of Gomel Region, where many thyroid cases were observed: the districts of Bragin, Khoiniki, Yelsk, Mozyr, and Narovlya, and parts of the districts of Kalinkovichi, Lelichitsa, Loev, and Rechitsa; (3) the Gomel-Mogilev Spot: in Gomel Region, Buda-Koshelev, Chechersk, Dobrush, Korma, and Vetka districts in the northeastern part of Gomel Region, to which must be added Bikhov, Cherikov, Krasnopolye and Slavgorod districts, as well as western parts of Kostyukovichi and Klimovichi districts from Mogilev Region; (4) the city of Gomel in Gomel Region; (5) the remainder of Gomel and Mogilev Regions (with the exception of the city of Mogilev); (6) the city of Mogilev in Mogilev Region; (7) Luninets, Pinsk, and Stolin districts in Brest Region; (8) the city of Minsk in Minsk Region; (9) Grodno Region as well as the remainder of Brest and Minsk Regions; and (10) Vitebsk Region. The geographical distribution of cases and controls according to the zone of residence at the time of the accident is given in Table 1, where it is shown that approximately 70% of childhood thyroid-cancer cases registered between 1986 and 1992 were among children living at the time of the accident in Gomel and Mogilev Regions, which were the most contaminated in

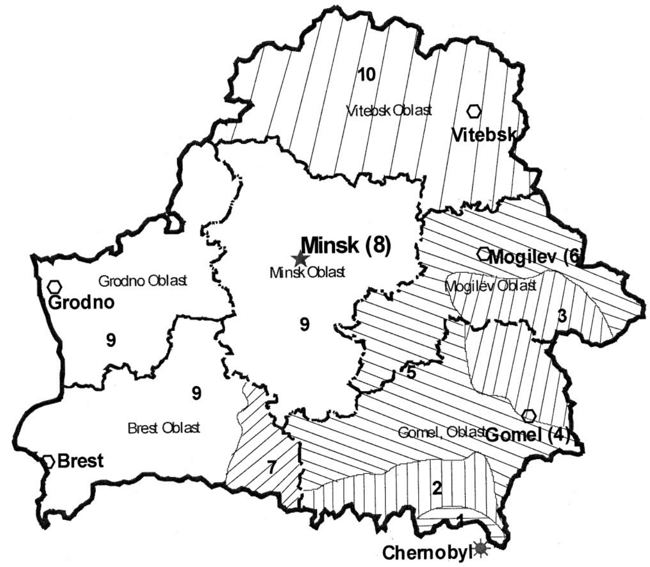

Fig. 1. Location of the 10 zones of the Republic of Belarus that are considered in the study and of the six administrative regions (Oblasts) of the country.

Table 1. Distribution of cases and controls according to their zone of residence at the time of the accident.[a]

Zone of residence		Number of cases	Number of controls
Number	Location		
1	30-km evacuated area	5	0
2	Southern part of Gomel Region	27	21
3	Gomel-Mogilev Spot	17	27
4	City of Gomel	19	13
5	Remainder of Gomel and Mogilev Regions	9	60
6	City of Mogilev	0	9
7	Eastern part of Brest Region	10	16
8	City of Minsk	5	20
9	Grodno Region and remainder of Brest and Minsk Regions	13	44
10	Vitebsk Region	2	4

[a] The locations of the zones of residence are shown in Fig. 1.

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the Republic of Belarus. Most (78 of 107, that is 73%) of the cases were less than 7 y of age at the time of the accident.

Dosimetry

Only thyroid doses resulting from intakes of ^{131}I and of short-lived radioiodines and radiotelluriums are estimated in this paper. Because the half-life of ^{131}I is about 8 d, the radionuclides under consideration decay to negligible levels in about 2 mo. Therefore, the thyroid dose due to ^{131}I and short-lived radioiodines and radiotelluriums had essentially been delivered by the end of June 1986. The assessment of the individual thyroid doses received by all subjects was carried out on the basis of (1) the knowledge of the whereabouts and dietary habits of the subjects between the time of the accident and the end of June 1986, which was obtained by means of personal interviews and mailed questionnaires, and (2) the relevant radiation information available for each subject or each area in which the subject resided during the 2 mo following the accident.

Personal interviews

In order to estimate individual thyroid doses for the cases and the controls, efforts were made to collect the following personal information on lifestyle and dietary habits during the first 2 mo after the Chernobyl accident:

- Consumption rates of the most important foodstuffs contributing to radioiodine intake: fresh milk, milk products and leafy vegetables;
- Origin of consumed foodstuffs;
- Changes in dietary habits after the accident;
- Residence at the time of the accident and during 2 mo afterwards (May–June 1986); and
- Intake of stable iodine for prophylactic reasons.

Individual information was collected for all 214 controls and 107 cases either in a personal interview, by mail, or in a telephone call. The information obtained from personal interviews was more complete and probably more reliable than that obtained by mail or in telephone calls. Because the personal information provided by the subjects had different degrees of completeness and quality, only the most reliable data (date of birth, place of residence at the time of the accident and in the following weeks, and date when the consumption of milk was interrupted) were used in order to estimate the individual thyroid doses.

Radiation information available

The children included in the case-control study can be classified into three basic groups according to the type of radiation information that is available for the assessment of their thyroid doses:

- Children with direct thyroid measurements made in May–June 1986 (12 cases and no controls); the estimates of thyroid doses that are derived from these direct thyroid measurements are called "measured" doses;
- Children without direct thyroid measurements but living in those settlements where a reasonably large number of inhabitants had direct thyroid measurements, and therefore the age distribution of average thyroid doses can be estimated for the children of those settlements with relatively good accuracy (51 cases and 58 controls); the thyroid doses estimated using this method are called "passport" doses; and
- Children without direct thyroid measurements and living in those settlements where such measurements were not carried out (78 cases and 86 controls); to assess thyroid doses for these children, a dosimetric model based on the relationship between measured ^{137}Cs deposition, or inferred ^{131}I deposition, and measured thyroid doses in comparable areas has been developed. Official information about country-wide ^{137}Cs deposition density (Hydrometeorological Committee 1992) and average ratio of ^{131}I-to-^{137}Cs activities in soil derived from results of measurements performed in May–July 1986 for about 600 settlements over the Belarusian territory (Dubina et al. 1990) were used to apply this method. The thyroid doses obtained in this manner are called "inferred" doses.

METHODS

Thyroid doses from internal irradiation arising from the intake of ^{131}I are as a rule substantially greater than those arising from the intake of short-lived radioiodines (^{132}I, ^{133}I, and ^{135}I) and radiotelluriums (^{131m}Te and ^{132}Te) and are considered separately.

Estimation of the thyroid doses due to intake of ^{131}I

The methods used to estimate "measured," "passport," and "inferred" individual thyroid doses resulting from the intake of ^{131}I are described in detail in Gavrilin et al. (1999). They will be summarized briefly in this paper.

Estimation of thyroid doses for children with in-vivo thyroid measurements ("measured" doses)

More than 200,000 radiation measurements against the necks of people were conducted in Belarus, mainly in the more contaminated areas, from the beginning of May to the middle of June 1986. These so-called "thyroid measurements" were aimed at the determination of the thyroidal ^{131}I content in Belarusian people in order to calculate the most reliable individual thyroid doses. Among the 12 cases with thyroid measurements, 10 were from rural areas of Gomel Region, one was from a rural area of Mogilev Region, and one was from the city of Minsk.

Survey meters with two types of detectors were used for the thyroid measurements of the 12 cases: (1) a Geiger-Muller counter, called DP-5, used for six of the cases; and (2) a NaI(Tl) crystal, called SRP-68-01, for the other six cases. All survey-meter indications were in terms of exposure rate.

The formula of thyroid dose calculation due to internal exposure from β-γ-rays of ^{131}I can be written as follows, for children with thyroid measurements:

$$D_1(i) = \alpha \times \frac{E_e(i)}{m(i)} \times G(t_{m,i}) \times F(t_{m,i}), \tag{1}$$

where

- $D_1(i)$ is the thyroid dose received by a child of age, i, in Gray;
- α is the number of seconds in a day ($=$ 86,400 s d^{-1});
- $E_e(i)/m(i)$ is the quotient of the average energy of β-γ radiation absorbed in the thyroid per radioactive decay of ^{131}I, in Joule, and of the mass of the thyroid, in kg; the numerical values of $E_e(i)/m(i)$ are based on data proposed in ICRP Publication 56 (ICRP 1990). The values of $E_e(i)/m(i)$ are in the range from 1.6×10^{-12} J kg^{-1} per radioactive decay of ^{131}I for the adult to 1.9×10^{-11} J kg^{-1} per radioactive decay of ^{131}I for the newborn;
- t_m is the time elapsed from the occurrence of ^{131}I fallout to the date of the thyroid measurements;
- $G(t_{m,i})$ is the ^{131}I content in the thyroid at the time of measurement t_m, Bq; and
- $F(t_{m,i})$ is the function describing the kinetics of ^{131}I content in the human thyroid, d.

Determination of the thyroidal ^{131}I content. The human thyroidal ^{131}I content $G(t_{m,i})$ at the time of measurement t_m was derived from the thyroid measurement, taking into account the background and the variation of the calibration coefficient with age.

Determination of the kinetics of ^{131}I content. The function describing the kinetics of ^{131}I content, $F(t_{m,i})$, depends on how ^{131}I was distributed in the environment after the accident and how people made use of the environment contaminated with ^{131}I. The two main pathways of human exposure to environmental ^{131}I are ingestion of contaminated fresh milk and inhalation of contaminated air. For the individuals who consumed fresh milk, only the milk pathway was taken into account because, on average, the ^{131}I inhalation intake was lower than the ^{131}I ingestion intake by a factor of at least 10. This was the case for the 12 subjects with thyroid measurement. It was assumed that none of the subjects took stable iodine pills in order to block the uptake of ^{131}I by the thyroid and that in each area considered the day when cows were first put onto pasture was before the main ^{131}I fallout occurred.

Estimation of thyroid doses derived by affinity ("passport" doses). In villages and small towns, where milk consumption accounted for most of the thyroid dose and where milk was usually obtained from a family cow, it can be assumed that the ^{131}I milk concentrations were relatively uniform throughout the village or the small town and therefore that the thyroid doses for individuals of a given age was a linear function of their milk consumption rate. For every village with a sufficient number of residents with measured thyroid doses, individual-thyroid-dose distributions have been determined for several age groups and several levels of milk consumption. This action has been called the "passportization" of the village with regard to thyroid exposure. The thyroid dose for any inhabitant from a village with "passportization" is derived by affinity with the measured doses for individuals of the same age, taking into consideration the milk-consumption rate and the length of time spent in the village after the accident. This method could be used for 51 of the 107 cases and for 58 of the 214 controls.

"Passport" doses have been calculated for more than 800 villages and small towns in Gomel and Mogilev Regions where there are at least 10 residents with "measured" thyroid doses. On the basis of the available "measured" doses, geometric mean "passport" thyroid doses have been estimated for the residents of these settlements: (1) for each of 19 age groups (one adult category and 18 age groups for children aged up to 18 y at the time of the accident, with incremental steps of 1 y), and (2) for 11 levels of milk consumption rate ranging from 0 L d^{-1} (inhalation intake only) to 4.0 L d^{-1}, as well as for a default level used when the information on the level of milk-consumption rate is absent. The default level of milk consumption rate was taken to be 0.4 L d^{-1} for children under 13 y of age, 0.5 L d^{-1} for teenagers between 13 and 15 y old, and 0.7 L d^{-1} for teenagers 16 and 17 y old and for adults.

The contribution to the thyroid dose due to ^{131}I intake with leafy vegetables is considered to be small for most individuals and has not been included into the thyroid dose estimation. Uncertainties have been assigned to the "passport" dose estimates, using the assumption that the individual thyroid dose distribution for the residents in the same age class in any settlement can be represented by a lognormal function.

"Passport" thyroid doses also have been estimated for four large cities (Minsk, Gomel, Mogilev, and Mozyr) where large numbers of residents have "measured" thyroid doses. The inhabitants of large cities consume milk from shops. No correlation was found between the milk consumption rates and the "measured" thyroid doses for residents of large cities of the same age, thus implying that the ^{131}I milk concentrations were highly variable from one part of the city to another. "Passport" thyroid doses for cases and controls from the four large cities were assumed to be equal to the geometric mean of the "measured" thyroid doses, for the same age category.

Estimation of thyroid doses based on ^{137}Cs deposition ("inferred" doses)

In the majority of villages of Belarus, either direct thyroid measurements were not performed or their number was less than 10. Under those conditions, "passport" doses cannot be estimated. Although the ^{131}I ground deposition densities are available for a number of villages (Dubina et al. 1990), the only environmental radiation measurement that is consistently available is the ground deposition density of ^{137}Cs. The thyroid doses received by people for whom there is no opportunity to obtain "measured" or "passport" thyroid doses have been derived from empirical relationships that were determined between the "measured" thyroid doses among adults and the ground deposition density of ^{137}Cs in villages with a sufficient number of in-vivo thyroid measurements. Such thyroid-dose estimates are denoted as "inferred" doses. This method has been used for all 107 cases and all 214 controls and is the only one that can be used for 44 cases and 156 controls.

The method of determination of the "inferred" doses is described in detail by Gavrilin et al. (1996a). The empirical relationships were established for relatively large territories where the time-integrated concentrations of ^{131}I in the air during the period of contamination are assumed to be the same. Both the average values of ground deposition density of ^{137}Cs and ^{131}I in the selected territory, x, and in the vicinity of the settlement, s, that is considered are used to assess the mean value of the thyroid dose, $D_{s,x}$, for rural adult residents in the settlement, s. As examples, the variation of the quotient of the estimated average thyroid dose for adults, $D_{s,x}$, and of the ground deposition as a function of $q_{s,x}$, is presented in Fig. 2 for the adult populations of settlements, s, of the Khoiniki district, x, in Gomel Region and of the Krasnopolye district in Mogilev Region. It can be seen in Fig. 2 that for small values of $q_{s,x}$ the values of $(D/q)_{s,x}$ decrease sharply as the values of $q_{s,x}$ increase and that the $(D/q)_{s,x}$ ratio is approximately constant within a relatively large range of ^{137}Cs deposition densities.

The thyroid doses for children $D_{s,x}(i)$ in age class i in village s of territory x are derived from those for adults $D_{s,x}(ad)$ in that village:

$$D_{s,x}(i) = D_{s,x}(ad) \times K(i), \tag{2}$$

where $K(i)$ is a dimensionless coefficient that takes into account the variation with age of the milk consumption rate, breathing rate, and thyroid dose coefficients for inhalation and ingestion. The estimated values for $K(i)$ are given in Table 2, assuming average milk consumption rate.

Estimation of uncertainties

The current estimates of the main sources of uncertainties in the estimation of the parameters involved in the determination of "measured," "passport," and "inferred" doses are presented in Table 3. Assuming that the parameter values are lognormally distributed, the distribution of each parameter, a, is characterized by its value of the geometric standard deviation, β_a. The geometric standard deviation, β_c, of the distribution of values of the product, c, of two parameters, a and b, is estimated as:

$$\beta_c = e^{\sqrt{\ln^2 \beta_a + \ln^2 \beta_b + 2\cdot \mathrm{cor}(a,b)\cdot \ln \beta_a \cdot \ln \beta_b}}, \tag{3}$$

where cor(a,b) is the correlation coefficient between the logarithms of the values of parameters a and b. Most of the input parameters listed in Table 3 can be considered to be independent, and, consequently, cor(a,b) = 0. However, there are important exceptions requiring the accurate description of the correlation between certain parameter values (Gavrilin et al. 1993).

"Measured" doses. The uncertainty in the "measured" dose is caused by the four independent quantities in eqn (1): the specific energy, $E_e(i)$; the thyroid mass, $m(i)$; the thyroidal ^{131}I content, $G(t_{m,i})$; and the temporal function of the ^{131}I rate of intake, $F(t_{m,i})$:

- the uncertainty in the specific energy is small in comparison to those associated with the other three parameters; it has been ignored in this assessment;
- the uncertainty in the thyroid mass is based on measurements and is taken to be associated with a geometric standard deviation (GSD) of 1.6 (Dunning and Schwarz 1981);
- the uncertainty in the thyroidal ^{131}I content, $G(t_{m,i})$, depends on the conditions of measurement. As the initial thyroid measurements were being processed, it appeared from discussions with the operators who conducted the measurements that the DP-5 instrument

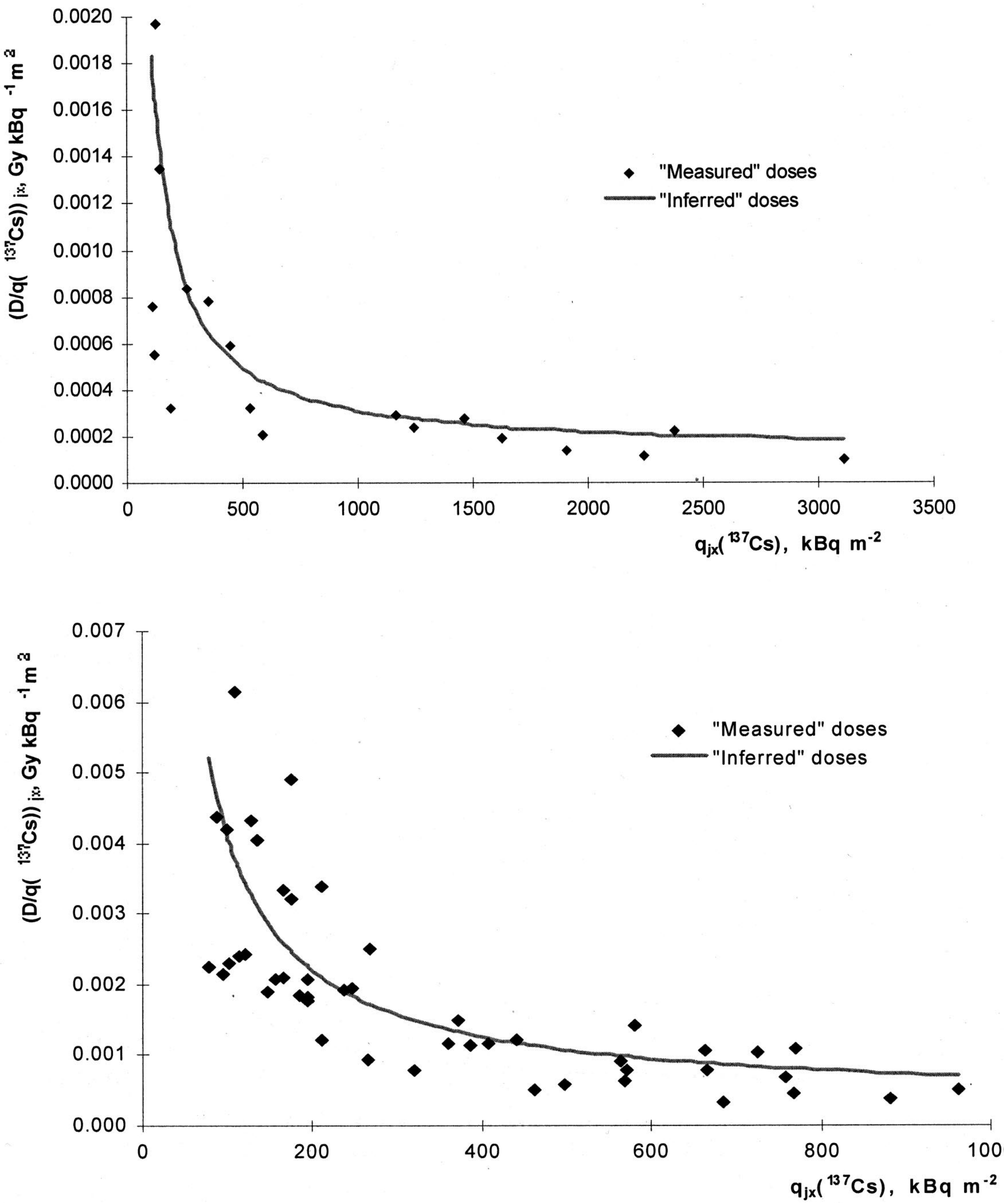

Fig. 2. Variation in the quotient of the estimated average thyroid dose for adults D_{jx} and of the ground deposition as a function of $q_{j,x}$. The top curve presents the values obtained for the adult population of villages, *j*, in the Krasnopolye district, *x*, of Mogilev Region; the bottom curve is related to the adult population of villages in the Khoiniki district of Gomel Region.

had been used under several operational conditions, and that it was not clear in many cases whether it had been used under the correct conditions ("standard geometry" of thyroid measurement), if the correct scale had been read, or if the result had been reported in the correct unit. Also, it often happened that the subjects had not washed themselves and/or wore contaminated clothes at the time of the thyroid measurement. Such uncertainties in the measurements made with the DP-5 instruments resulted in additional errors in the determination of the ^{131}I thyroidal content in comparison with the measurements made with the

Table 2. Estimated values of the dimensionless coefficient $K(i)$.

Age, i	0–1	1–2	2–3	3–4	4–5	5–6	6–7	7–8	8–9	9–10	10–11
$K(i)$	5.6	4.3	3.7	2.6	2.2	2.0	1.8	1.6	1.4	1.3	1.2

SRP-68-01 instruments in hospitals when the subjects had washed themselves and contaminated clothes had been removed before the measurements were conducted. Three groups of reliability were introduced by Gavrilin et al. (1992) to reflect different conditions of determination of the thyroidal ^{131}I content: Group 1 (highest reliability), Group 2 (intermediate reliability), and Group 3 (lowest reliability). For Group 1, the GSD of the distribution of the values of $G(t_{m,i})$ is assessed at 1.3 taking into account the variation of the calibration coefficient as a function of individual variability of the thickness of the tissue overlapping the thyroid and of geometrical size of the thyroid. Uncertainties for Groups 2 and 3 were evaluated empirically by analyzing the distribution of ratios Group 2/Group 1 (or Group 3/Group 1) for the same persons (a set of about 300 pairs of results was analyzed); the corresponding geometrical standard deviations of the distributions of the values of $G(t_{m,i})$ are estimated to be 1.3–1.7 and 1.7–2.2 for measurements in Group 2 and Group 3, respectively; and

- the uncertainty in the function $F(t_{m,i})$ was evaluated by means of numerical modeling of different conditions of contamination of pasture grass and soil, and for different dates of beginning of pasture season; the corresponding GSDs were found to range from 1.2 to 1.4, taking into account the facts that most of the direct thyroid measurements were made at least 1 wk after the beginning of the pasture season and that a simplified one-exponential model was considered for iodine retention in the cow instead of a more complex model like, for example, that of Garner (1967).

Thus, the final estimates are 1.7–1.8 for the Group 1 of "measured" doses, 1.8–2.1 for Group 2, and 2.1–2.6 for Group 3, assuming an absence of correlation between the three parameters.

Table 3. Individual thyroid dose assessment: estimates of geometric standard deviation (GSD) for the input parameters and for the resulting dose estimates.

Parameter	Geometric standard deviation
"Measured" doses:	
1. Input parameters:	
Thyroid mass, m (Dunning and Schwarz 1981)	1.6
Thyroidal ^{131}I content, $G(t_m)$ (empirical estimation)	1.3 (Group 1) 1.3–1.7 (Group 2) 1.7–2.2 (Group 3)
Temporal variation of ^{131}I intake, $F(t_m)$	1.2–1.4
2. Resulting doses:	
Individual "measured" dose	1.7–1.8 (Group 1) 1.8–2.1 (Group 2) 2.1–2.6 (Group 3)
"Passport" doses:	
1. Input parameters:	
Geometric mean "passport" dose for the residents of a given age group in the settlement	1.4–1.6
Daily milk consumption (for each age group)	1.6
^{131}I concentration in milk	1.3–1.8
Thyroid dose factor, DF (Dunning and Schwartz 1981)	1.8
2. Resulting doses:	
Individual "passport" dose (unknown milk consumption)	2.4–2.9
Individual "passport" dose (known milk consumption $\neq 0$)[a]	2.1–2.6
"Inferred" doses:	
1. Input parameters:	
Average "inferred" dose for the residents of a given age group in the settlement	1.6–1.8
2. Resulting doses:	
Individual "inferred" dose (unknown milk consumption)	2.5–3.1
Individual "inferred" dose (known milk consumption)	2.2–2.8

[a] The geometric standard deviation is estimated to be 3.4 for the doses from inhalation only.

"Passport" doses. The uncertainties associated with the estimates of the "passport" doses can be related to one of two groups: (1) uncertainty in the determination of the mean value of the "passport" dose for the residents of a given age group in the settlement, and (2) uncertainty due to insufficient knowledge regarding the values, for the individual considered, of the ^{131}I intake, the ^{131}I uptake by the thyroid, the thyroid mass, and the half-time of residence of ^{131}I in the thyroid.

The random error in the uncertainty of the mean value of the "passport" dose for the residents of a given age group in the settlement is taken to be characterized by a GSD of 1.4–1.6. This uncertainty is relatively low because of the requirement for the number of individual "measured" doses used to estimate the mean to be greater than 10. Some systematic uncertainty in the estimate of the mean value cannot be excluded for a number of settlements, for instance, because of the nonrepresentativity of the available "measured" doses. However, a dispersion analysis of the available data showed that this error is negligible for most of the "passportized" settlements under consideration (Gavrilin et al. 1996c).

Errors associated with the assessment of individual doses are due to several reasons, the most important of which are different ^{131}I concentrations in milk of private cows, different individual milk consumption rates, thyroid masses, and individual uptakes of ^{131}I by the thyroid. The uncertainty in the individual intake of ^{131}I is taken to be represented by a GSD of 1.6, while the uncertainty in the thyroid dose factor is assumed to have a GSD of 1.8, in accordance with the results of Dunning and Schwarz (1981). However, because Dunning and Schwarz assume that the thyroid mass and the iodine uptake by the thyroid of a given individual are not correlated, the uncertainties presented in Table 3 may be overestimated.

For individuals with unknown milk consumption rates, the uncertainty in the thyroid dose is characterized by an estimated GSD of 2.4–2.9. The individual uncertainty can be decreased if the individual daily milk consumption is known relatively accurately as an outcome of the personal interview. In that case, the uncertainty associated with the individual milk consumption rate (GSD of 1.6) may not be taken into account, so that the uncertainty attached to the individual thyroid dose is characterized by a GSD ranging from 2.1 to 2.6.

"Inferred" doses. As for the "passport" doses, the uncertainties associated with the estimates of the "inferred" doses can be related to one of two groups: (1) uncertainty in the determination of the mean value for the residents of a given age group in the settlement, and (2) uncertainty caused by individual variability of ^{131}I intake, of ^{131}I uptake in the thyroid, and of ^{131}I clearance from the thyroid.

The GSD of 1.6–1.8 related to the uncertainty attached to the mean "inferred" dose was estimated empirically by comparing adult doses calculated by the method described in Gavrilin et al. (1996b) and average adult "measured" doses for about 300 of the most representative settlements of Belarus and Russia. The distribution of the ratio of the doses was found to be approximately lognormal.

The uncertainties resulting from individual variability are the same for the "passport" and for the "inferred" doses. The overall uncertainties attached to the estimates of "inferred" doses are characterized by GSDs of 2.2 to 2.8 if the milk consumption rate is relatively well known and 2.5 to 3.1 if the milk consumption rate is unknown.

Availability of another model of thyroid dose estimation

It is worth noting that another model of thyroid dose estimation was developed in Belarus (Drozdovitch et al. 1997). This model simulates the transfer of ^{131}I through environmental processes from ground deposition to intake by humans. The following radioecological parameters were estimated for the local conditions: (a) ratio of ^{131}I and ^{137}Cs in the activities deposited on the ground; (b) stage of vegetation development; (c) initial interception of ^{131}I by vegetation; (d) elimination rate of ^{131}I from grass and milk; and (e) age-dependent milk consumption rates. Additionally, the influence of applied countermeasures (evacuation, introduction of maximum permissible level of ^{131}I concentration in milk) was taken into account.

To verify the validity of the model, results of calculation were compared with available results of direct thyroid measurements performed in May–June 1986. For 95% of the villages with more than 15 direct thyroid measurements, the results of the radioecological model and of the direct thyroid measurements were found to agree within a factor of 3 (Drozdovitch et al. 1997).

This radioecological model was not used to estimate the thyroid doses for the cases and controls as it had not been fully developed at the time of the study.

ESTIMATION OF THYROID DOSES RESULTING FROM THE INTAKE OF SHORT-LIVED RADIOIODINES AND RADIOTELLURIUMS

From the dosimetric point of view, ^{131}I is the most important radioiodine. However, ^{131}I is not the only radioiodine that is produced in a nuclear reactor. Three shorter-lived radioiodines [^{132}I (half-life: 2.3 h), ^{133}I (half-life: 20.8 h), and ^{135}I (half-life: 6.6 h)], which behave in the reactor, the environment, and the body like ^{131}I, have been considered, along with two radiotelluriums [^{131m}Te (half-life: 30 h) and ^{132}Te (half-life: 78.2 h)] that are the precursors of radioiodines.

The methodology described here is based on the work of Gavrilin et al. (1991). The ratio of the thyroid dose D_{sl} (Gy) resulting from intake of all short-lived radioiodines and radiotelluriums and of the thyroid dose from ^{131}I alone, D_1, for a child of age i can be calculated according to

$$\frac{D_{sl}(i)}{D_1(i)} = \frac{D_{1,p}(i)}{D_1(i)} \times \sum_k f_{p,k}(i) \times w_{p,k}(i) + \frac{D_{1,h}(i)}{D_1(i)} \times \sum_k f_{h,k}(i) \times w_{h,k}, \quad (4)$$

where:

$D_{1,p}(i)$ and $D_{1,h}(i)$ = the internal thyroid doses for a child of age i from ingestion and inhalation intake of ^{131}I, respectively, in Gy;

$D_1(i) = D_{1,p}(i) + D_{1,h}(i)$;

$f_{p,k}$ and $f_{h,k}$ = the ratios of the dose coefficients for ingestion and inhalation, respectively, for radionuclide k and for ^{131}I; and

$w_{p,k}(i)$ and $w_{h,k}(i)$ = the ratios of the intakes from ingestion and inhalation, respectively, for radionuclide k and for ^{131}I.

Estimation of the dose-coefficient ratios, $f_{p,k}(i)$ and $f_{h,k}(i)$

Values of the dose-coefficient ratios for the five short-lived radioisotopes of iodine and tellurium and for various ages were derived from data presented in ICRP Publications (ICRP 1993a, 1995, 1996). Results are presented in Table 4. The dose-coefficient ratios show little variation with age. For a given age, the dose-coefficient ratios vary mainly as a function of their physical half-lives. The dose-coefficient ratios for the radiotelluriums include the contributions of their decay products (radioiodines). The ^{131}I dose-coefficient values are also provided in Table 4.

Estimation of the intake ratios, $w_{p,k}(i)$ and $w_{h,k}$

A number of parameters are involved in the estimation of the values of $w_{p,k}$ and $w_{h,k}$:

1. the relative activities in the reactor core at the time of the accident;
2. the relative activities released from the reactor during the 10 days of release;
3. the relative activities deposited on the ground at the locations where thyroid doses are calculated;
4. the relative time-integrated concentrations in ground-level air at the locations where thyroid doses from inhalation are calculated; and
5. the transfer from ground (and vegetation) to human intake.

Each of those parameters will be considered in turn.

Relative activities in the reactor core at the time of the accident. The relative quantity of the short-lived radioiodines and radiotelluriums in the reactor core at the time of the accident is different from the distribution of those radionuclides at the time of a nuclear weapons test explosion. In the core of a reactor operating at a steady power level, the radionuclide inventories increase with time according to their fission yield and to their radioactive half-life; in the case of the radioiodines and radiotelluriums of interest, the inventories reach a steady state after a few days (for ^{133}I) to 1 month (for ^{131}I) of operation. This is why the mixture of radionuclides in the core of a reactor is enriched in relatively long-lived radionuclides, when compared to the distribution produced in a nuclear weapons test.

The power level of Unit 4 of the Chernobyl reactor varied substantially during the last day before the accidental explosion. This variation in power level, which has been described in detail (Chernobyl 1992), is presented in Table 5.

Ratios of activity of iodine and tellurium radioisotopes to activity of ^{131}I at time $t = 0$ (the moment of explosion: 01:24 a.m. Moscow time) have been calculated on the basis of primary equilibrium ratio values presented by Kolobashkin et al. (1983), taking into

Table 4. Thyroid dose-coefficient ratios for inhalation[a] ($f_{h,k}$) and ingestion[b,c] ($f_{p,k}$) intake of radioisotopes of iodine and tellurium as a function of age (ICRP 1993a, 1995, 1996).

Age group (y)	^{131}I thyroid dose coefficient (Gy Bq^{-1})	^{132}I	^{133}I	^{135}I	^{131m}Te	^{132}Te
		Inhalation: dose-coefficient ratio to ^{131}I, $f_{h,k}$				
0–1	1.4 10^{-6}	0.013	0.27	0.055	0.10	0.26
1–2	1.4 10^{-6}	0.011	0.25	0.050	0.086	0.21
3–7	7.3 10^{-7}	0.010	0.22	0.045	0.088	0.19
8–12	3.7 10^{-7}	0.0092	0.20	0.041	0.089	0.16
13–17	2.2 10^{-7}	0.0095	0.20	0.040	0.091	0.17
Adult	1.5 10^{-7}	0.0093	0.19	0.038	0.082	0.17
		Ingestion: dose-coefficient ratio to ^{131}I, $f_{p,k}$				
0–1	3.7 10^{-6}	0.011	0.27	0.056	0.070	0.17
1–2	3.6 10^{-6}	0.0097	0.24	0.049	0.042	0.083
3–7	2.1 10^{-6}	0.0090	0.23	0.047	0.042	0.076
8–12	1.0 10^{-6}	0.0083	0.19	0.042	0.045	0.071
13–17	6.8 10^{-7}	0.0079	0.20	0.041	0.043	0.068
Adult	4.3 10^{-7}	0.0079	0.20	0.042	0.044	0.067

[a] The thyroid dose-coefficient ratios for inhalation of all radionuclides are taken from ICRP (1995). Type F absorption of 1-μm aerosols has been assumed for the inhalation of all radioiodines and radiotelluriums.
[b] The thyroid dose-coefficient ratios for ingestion of ^{132}I, ^{131m}Te, and ^{132}Te are taken from ICRP (1993a).
[c] The thyroid dose-coefficient ratios for ingestion of ^{133}I and ^{135}I are derived from data in ICRP (1996), assuming that the thyroid dose-coefficient ratios are equal to the effective dose-coefficient ratios.

Table 5. Variation in the thermal power of Unit 4 of the Chernobyl reactor during the last day before the explosion (Chernobyl 1992).

Time before the explosion, min	Variation of power	Initial thermal power, MW	Final thermal power, MW
Greater than 1458	Constant	3,200	3,200
Between 1458 and 1297	Decrease	3,200	1,600
Between 1297 and 134	Constant	1,600	1,600
Between 134 and 79	Decrease	1,600	720
Between 79 and 56	Decrease	720	500
At 56	Decrease	500	30
Between 56 and 49.95	Constant	30	30
Between 49.95 and 21	Increase	30	200
Between 21 and near 0	Constant	200	200
Power surge[a]	See footnote a	200	—

[a] The thermal power rose very quickly just before the explosion to a value equal to 3.5 to 80 times the nominal power; the duration of this power surge was about 4 to 5 s.

account the variation in power level (Table 5) during the last day before the explosion. The changes of power during the last day before the explosion affected only slightly (3%) the activity of ^{131}I but had a more important effect for short-lived radionuclides. For example, the ^{133}I to ^{131}I activity ratio was lower at the time of the explosion than 1 day before by a factor of approximately 1.3. The power surge during the last few seconds before the explosion is not thought to have been sufficient to change substantially the quantity of the main radionuclides of interest in this paper. However, it is possible that the role of the power surge will be found to have been vastly underestimated in a reevaluation of the accident scenario; if that were true, the role of the short-lived radionuclides would have to be revised upwards. The values of the activity ratios calculated for the purposes of this paper are presented in Table 6, along with values published by Ermilov and Ziborov (1993) for ^{133}I and ^{132}Te.

Relative activities released from the reactor during the 10 days of release. Radionuclides were released in varying amounts during the ten days that followed the initial explosion. The ratios shown in Table 6 of the radionuclide activities present in the reactor core at the moment of the explosion are likely to be upper bounds of the ratios of the activities released during the 10 days of the accident because (1) all radionuclides considered have half-lives shorter than that of ^{131}I, and, consequently, their ratios to ^{131}I decreased as a function of time elapsed since the initial explosion, and (2) the radiotelluriums are not as volatile as the radioiodines, and, consequently, were not released from the reactor as effectively as the radioiodines. According to Sivintsev and Khrulev (1995), the activity ratio of ^{132}Te to ^{131}I in the releases that occurred during the first day of the accident is estimated to be 0.8–0.9, whereas the activity ratio of ^{132}Te to ^{131}I in the overall releases during the 10 days of the accident is approximately 0.2.

Relative activities deposited on the ground at the locations where thyroid doses are calculated. Because the radioactive releases lasted about 10 days and the wind speed and direction changed considerably during those 10 days, the relative activities deposited on the ground are not constant as they depend on the time of release of the radioactive cloud responsible for the contamination of the ground at the location considered and on how much time it took for that radioactive cloud to reach the location considered. In addition, the efficiency of the scavenging processes from the atmosphere to the ground may have been different for radioiodines and for radiotelluriums, both for dry and for wet deposition. It is to take these large differences from an area to another into account that the territory of the Republic of Belarus was subdivided into 10 zones, as shown in Fig. 1.

If the measured daily fallout of ^{131}I and of a given radionuclide, k, are available, the relative activity, r_k, of that radionuclide deposited on the ground to that of ^{131}I can be estimated according to

$$r_k = \frac{\sum_j \sigma_{k,j}}{\sum_j \sigma_{I,j}}, \quad (5)$$

where $\sigma_{I,j}$ and $\sigma_{k,j}$ are the values of fallout for day j for ^{131}I and radionuclide k, respectively.

Measured data are not available for short-lived isotopes of iodine (^{133}I and ^{135}I) or for ^{131m}Te. However, it is reasonable to assume that the activity ratio of ^{133}I or of ^{135}I to ^{131}I in the environment decreased in time after the reactor explosion according to the laws of radioactive decay. The same is true for the activity ratio of ^{131m}Te to ^{132}Te.

Measured daily fallout of ^{131}I in the Belarusian cities of Gomel, Minsk, and Mogilev (Makhon'ko et al. 1996)

Table 6. Ratios of radionuclide activity to activity of ^{131}I in the reactor core at the time of the explosion.

Radionuclide	^{132}I	^{133}I	^{135}I	^{131m}Te	^{132}Te
Ratio (Ermilov and Ziborov 1993)		1.57			1.45
Ratio (this paper)	1.33	1.48	0.91	0.18	1.30

can be used for the estimation of $\sigma_{1,j}$. For the other locations of interest in Belarus, assumptions or expert estimates regarding the relative distribution with time of the ^{131}I fallout have been made on the basis of fallout data (Izrael et al. 1990; Makhon'ko et al. 1996) and of rainfall data (Germenchuk 1999***). The estimated daily deposition densities of ^{131}I, ϵ_j, expressed as percentages of the total ^{131}I activities deposited per unit area of ground, are shown in Table 7. The fallout kinetics of ^{133}I and of ^{135}I were derived from the measured or estimated deposition densities of ^{131}I, the resulting deposition density ratios r_k, relative to ^{131}I, are presented in Table 8.

A reliable estimation of the daily depositions of ^{132}Te (relative to ^{131}I) is more difficult because measured results of ^{132}Te in fallout are available mainly for the southern territories of Gomel Region (zones 1 and 2) and are not consistent for some of the other zones. Expert estimates have been made on the basis of fallout data (Dubina et al. 1990; Makhon'ko et al. 1996). For all areas under consideration, it has been assumed that the variation with time of the ground deposition of ^{132}Te is the same as that of ^{131}I. This seems reasonable because the data of Makhon'ko et al. (1996) show a high degree of correlation between the daily fallout values of ^{131}I and of ^{132}Te + ^{132}I for the cities of Baranovichi, Gomel, and Pinsk (the correlation coefficient is greater than 0.97). Results are presented in Table 8. The ratios of ^{132}Te and ^{131}I in fallout are then used to calculate the fallout of ^{131m}Te, relative to ^{131}I. The estimated ratios of the deposition densities r_k, relative to ^{131}I, for the considered radionuclides and for all areas of Belarus are summarized in Table 8.

*** Personal communication: Germenchuk MG. Republican Center for Environmental Control and Radiation Monitoring, 110A Skaryna Avenue, Minsk 220023; Belarus; 1999.

Relative time-integrated concentrations in ground-level air. The estimated activity ratios of ^{133}I and ^{135}I relative to ^{131}I for the deposition densities may be used also as estimates of the ratios of time-integrated concentrations in ground-level air. However, this may not be true for the ratios of radiotelluriums; the relative ratios estimated for the deposited activities may not reflect the ratios of the time-integrated concentrations in ground-level air because of possible differences in the scavenging efficiencies of tellurium and iodine from air to ground as a result of dry or of wet deposition. Tellurium was likely to be predominantly attached to aerosols, while iodine was present in various forms: (1) elemental, which would be deposited more readily than aerosols in the case of dry deposition; (2) organic, which would deposit much less than aerosols; and (3) aerosols. The dry deposition velocity of elemental iodine is estimated to be greater than that of aerosols by a factor of 6 to 10 (Müller and Pröhl 1993). Therefore, the deposited mixture of radionuclides would be enriched by tellurium if the fraction of elemental iodine in air was less than 0.1–0.2. On the contrary, the deposited mixture could be enriched by iodine if the fraction of elemental iodine was more than 0.1–0.2. Unfortunately, the actual fraction of elemental and organic radioiodine in the air is unknown for the areas under consideration. In the absence of information on the concentrations of radioiodines and radiotelluriums in the ground-level air for the areas under consideration, it has been assumed that the ratios of the time-integrated concentrations of radionuclides in the ground-level air are equal to those estimated for the dry deposited activities (zones 1, 2, 4, 7, 9, and 10).

In the case of wet fallout, the activity ratio of ^{132}Te and ^{131}I on the ground is greater than in the air because aerosols are captured by rainwater more efficiently than

Table 7. Estimated kinetics of ^{131}I fallout in the ten zones of residence.

Time interval [month/day(hour)]	Daily percentage of total ^{131}I fallout in each zone, $100 \times \varepsilon_j$									
	1	2	3	4	5	6	7	8	9	10
4/26 (1:24 a.m.)–4/26 (8 a.m.)	50	1.2		0.003	0.11	0.11	0.04	0.1	0.2	1.28
4/26 (8 a.m.)–4/27 (8 a.m.)	50	26.5		0.014	0.11	0.11	0.28	0.1	7.6	0.33
4/27 (8 a.m.)–4/28 (8 a.m.)		42.6	90[a]	0.364	31.57[a]	31.57[a]	74.15	1.4	57.2	0.14
4/28 (8 a.m.)–4/29 (8 a.m.)		17.4	9.2	91.576	46.03[a]	46.03[a]	18.5	51.5[a]	18.7	1.29[a]
4/29 (8 a.m.)–4/30 (8 a.m.)		3.3	0.6	6.075	2.03	2.03	2.85	17.8	8.7	3.58
4/30 (8 a.m.)–5/1 (8 a.m.)		3.3	0.2	0.539	6.93	6.93	1.31	10.6	3.3	35.1
5/1 (8 a.m.)–5/2 (8 a.m.)		1.7		0.264	4.38	4.38	0.51	3.8	0.9	23.96
5/2 (8 a.m.)–5/3 (8 a.m.)		2.9		0.035	1.68	1.68	0.41	1.2	0.2	7.51
5/3 (8 a.m.)–5/4 (8 a.m.)		0.6		0.22	1.43	1.43	0.22	1.2	0.3	1.67
5/4 (8 a.m.)–5/5 (8 a.m.)		0.5		0.08	0.32	0.32	0.11	0.6	0.3	6.91
5/5 (8 a.m.)–5/6 (8 a.m.)				0.07	0.73	0.73	0.09	0.4	0.1	3.45
5/6 (8 a.m.)–5/7 (8 a.m.)				0.06	0.52	0.52	0.1	0.3	0.02	5.91
5/7 (8 a.m.)–and later				0.7	4.16	4.16	1.43	11	2.48	8.87
Total	100	100	100	100	100	100	100	100	100	100

[a] The daily rainfall was greater than 1 mm according to data of Belhydromet.

Table 8. Estimates of ratios r_k, relative to ^{131}I, of the deposition densities of the short-lived radioiodines and radiotelluriums, and of the time-integrated concentrations of radionuclides in ground-level air ($w_{h,k}$).

Zone number	^{131m}Te	^{132}Te	^{132}I [a]	^{133}I	^{135}I
			Deposition-density ratios		
1	0.10	0.8	0.8	1.1	0.40
2	0.04	0.5	0.5	0.47	0.061
3[b]	0.10	1.3	1.3	0.41	0.014
4	0.008	0.15	0.15	0.20	0.001
5[b]	0.011	0.2	0.2	0.24	0.006
6[b]	0.011	0.2	0.2	0.24	0.006
7	0.028	0.4	0.4	0.36	0.012
8[b]	0.008	0.2	0.2	0.14	0.001
9	0.034	0.5	0.5	0.36	0.024
10	0.004	0.2	0.2	0.05	0.008
			Ground-level air concentration ratios ($w_{h,k}$)		
1	0.10	0.8	0.8	1.1	0.40
2	0.04	0.5	0.5	0.47	0.061
3[b]	0.025	0.3	0.3	0.41	0.014
4	0.008	0.15	0.15	0.20	0.001
5[b]	0.003	0.05	0.05	0.24	0.006
6[b]	0.003	0.05	0.05	0.24	0.006
7	0.028	0.4	0.4	0.36	0.012
8[b]	0.002	0.05	0.05	0.14	0.001
9	0.034	0.5	0.5	0.36	0.024
10	0.004	0.2	0.2	0.05	0.008

[a] In radioactive equilibrium with ^{132}Te.
[b] Wet deposition, which took place mainly on April 28 (see Table 7).

elemental or organic radioiodine. In the absence of data, the numerical value of the factor by which the activity ratio of ^{132}Te and ^{131}I on the ground needs to be divided to obtain the activity ratio of ^{132}Te and ^{131}I in the air has been taken to be equal to 4. This applies to all areas where wet fallout was substantial (zones 3, 5, 6, and 8).

The estimated ratios of the time-integrated concentrations in ground-level air are presented in Table 8 for all areas of Belarus.

In addition, the ratio of the dose from inhalation, $D_{1,h}$, and of the total thyroid dose from ^{131}I, D_1, needs to be estimated for its use in eqn. (4). This ratio is age-dependent because the breathing rate and the rate of milk consumption vary as a function of age.

For adults the following values of the ratios $D_{1,h}(ad)/D_1(ad)$ were taken for the 10 zones of Belarus:

- In villages where no countermeasure was applied, the ratio $D_{1,h}(ad)/D_1(ad)$ was taken to be equal to 0.05 (zones 3, 5, 7, 9, and 10);
- The population of the Belarusian villages of the 30-km zone (zone 1) was evacuated between 3 and 5 May 1986. Since only about 50% of the potential ^{131}I intake via milk consumption was realized at those dates, the ratio $D_{1,h}(ad)/D_1(ad)$ is thus equal to about 0.1 for that population;
- Children of the southern districts of Gomel Region (zone 2) were relocated (to pioneer camps and other places) on 7 May 1986. Accordingly, the value of $D_{1,h}(ad)/D_1(ad)$ was taken to be 0.08;
- For the cities of Gomel (zone 4) and Mogilev (zone 6), a ratio $D_{1,h}(ad)/D_1(ad)$ of 0.5 was applied on the assumption that the dose from inhalation was relatively more important in cities than in rural areas; and
- In the city of Minsk (zone 8), the dose from inhalation, $D_{1,h}(ad)$, was derived from the measured concentrations of ^{131}I in the air. According to data presented by Izrael et al. (1990), about 1.2 kBq was inhaled by the adult residents of Minsk. However, it is realistic to assume that the efficiency of filtration for radioiodine was only about 30% because of the presence of organic and elemental forms, which were not captured by the filters. Taking this into account, the inhalation dose would be about 1 mGy. In comparison, the average "measured" thyroid dose for adults in the city of Minsk was found to be 18 mGy. Therefore, the ratio $D_{1,h}(ad)/D_1(ad)$ is estimated to be equal to 0.06 for the population of the city of Minsk. The large difference obtained in the values of the $D_{1,h}(ad)/D_1(ad)$ ratio for the cities of Minsk on the one hand and Gomel and Mogilev on the other may arise from different sources of milk supply.

Because the consumption of cow's milk was the main source of ^{131}I intake, a simplified relationship was used to lead to the determination of the ratio of these doses for a child of age i to those for an adult:

$$\frac{D_{1,h}(i)/D_1(i)}{D_{1,h}(ad)/D_1(ad)} \approx \frac{M_{air}(i)/M_{mk}(i)}{M_{air}(ad)/M_{mk}(ad)}, \qquad (6)$$

where $M_{air}(i)$ is the breathing rate, $m^3\ d^{-1}$, of a child of age i, and M_{mk} is the milk consumption rate, L d^{-1}, of a child of age i.

The average breathing rates were extracted from ICRP 66 (1993b), whereas the milk consumption rates are based on results of personal interviews conducted among rural people in Belarus and presented above in the section on "passport" doses. For urban citizens, the milk consumption rates were taken to be 0.7 L d^{-1} for children under 1 y of age, 0.3 L d^{-1} for teenagers, and 0.2 L d^{-1} for adults (Anonymous 1989). Intermediate values were used for other age groups.

Estimates of the age-dependent dose ratios $D_{1,h}(i)/D_1(i)$ obtained using eqn (6) are presented in Table 9.

Estimation of human intake of short-lived radioiodines and radiotelluriums (relative to ^{131}I). Human intake of radioiodines can occur via several pathways: inhalation, consumption of fresh cow's or goat's milk, consumption of leafy vegetables, licking contaminated hands, absorption through skin, etc. The intake due to absorption through skin has been shown to be negligible (Margulis 1988). In the estimation of the thyroid doses from ^{131}I, the consumption of fresh cow's milk is the predominant pathway. In the estimation of the thyroid doses from short-lived radioiodines and radiotelluriums, because the consumption of fresh cow's milk is not as dominant as it is for ^{131}I, all major pathways (inhalation, the consumption of fresh cow's milk, the consumption of leafy vegetables, and the intakes arising from licking contaminated hands) have been considered in detail.

The ratios of the intakes from inhalation, relative to ^{131}I, $w_{h,k}$, are simply equal to the estimated ratios of the time-integrated concentrations in the air that are presented in Table 8. Their values are independent of the age of the subject i.

The ratios of the intakes from ingestion, relative to ^{131}I, $w_{p,k}(i)$, were derived from the time-integrated concentrations of radionuclides in milk, $IC_{mk,k}$, in leafy vegetables, $IC_{lv,k}$, and on hands, $IC_{hd,k}$, taking into account the age-dependent consumption rates of milk, $M_{mk}(i)$, of leafy vegetables, $M_{lv}(i)$, and the effective area of hands licked per day, $S_{hd}(i)$:

$$w_{p,k}(i) = \frac{1 + [M_{lv}(i)/M_{mk}(i)] \times (IC_{lv,k}/IC_{mk,k}) + [S_{hd}(i)/M_{mk}(i)] \times (IC_{hd,k}/IC_{mk,k})}{1 + [M_{lv}(i)/M_{mk}(i)] \times (IC_{lv,1}/IC_{mk,1}) + [S_{hd}(i)/M_{mk}(i)] \times (IC_{hd,1}/IC_{mk,1})} \times \frac{IC_{mk,k}}{IC_{mk,1}}. \tag{7}$$

The parameter values were selected as follows:

- The default values of daily milk consumption, $M_{mk}(i)$, are those indicated in the section on passport doses;
- The default values of daily consumption of leafy vegetables for early spring conditions, $M_{lv}(i)$, were taken to be 0 kg d^{-1} for infants under 1 year of age, 0.015 kg d^{-1} for children between the ages of 1 and 2 y, 0.020 kg d^{-1} for those between the ages of 3 and 7 y, 0.025 kg d^{-1} for those between the ages of 8 and 12 y, and 0.030 kg d^{-1} for persons of 13 y and older (Anonymous 1989; Rupp 1980; Tikhomirov 1983).
- The default values of the effective area of contaminated hands, $S_{hd}(i)$, were taken to be 0 m^2 for infants, 0.0033 m^2 for those between the ages of 1 and 2 y, 0.0052 m^2 for whose between the ages of 3 and 7 y, 0.0073 m^2 for those between the ages of 8 and 12 y, and 0.0132 m^2 for those between the ages of 13 and 17 y (Margulis 1988).

Estimation of the time-integrated concentration of radionuclides in leafy vegetables

The activity initially retained on the surface of leafy vegetables was assumed to decrease exponentially as a result of radioactive decay, of weathering processes, and of biomass increase (Müller and Pröhl 1993). Taking into account that fallout may have occurred over several days and that some activity is lost during culinary processes, the time-integrated concentration $IC_{lv,k}$ of radionuclide k

Table 9. Estimates of the age-dependent dose ratios $D_{1,h}(i)/D_1(i)$.

Zone number	Age i, y					
	0–1	1–2	3–7	8–12	13–17	Adult
1	0.019	0.026	0.074	0.14	0.14	0.1
2	0.015	0.021	0.059	0.11	0.11	0.08
3[a]	0.010	0.013	0.037	0.070	0.070	0.05
4	0.020	0.026	0.105	0.205	0.335	0.5
5[a]	0.010	0.013	0.037	0.070	0.070	0.05
6[a]	0.020	0.026	0.105	0.205	0.335	0.5
7	0.010	0.013	0.037	0.070	0.070	0.05
8[a]	0.002	0.003	0.013	0.025	0.040	0.06
9	0.010	0.013	0.037	0.070	0.070	0.05
10	0.010	0.013	0.037	0.070	0.070	0.05

[a] Areas with substantial wet deposition.

in consumed leafy vegetables can be estimated as follows:

$$IC_{lv,k} = k_w \times e^{-\lambda_k \cdot \tau} \times \sum_{j=0}^{N} \frac{\varepsilon_j \cdot a_{k,j} \cdot \eta_{k,j}}{\lambda_g + \lambda_k} \times [1 - e^{-(\lambda_g + \lambda_k)(N-j)}], \quad (8)$$

where:

k_w = 0.6 is the fraction of radionuclide remaining after culinary preparation (Anonymous 1989);
τ = is the delay between harvest and consumption, taken to be 0 d for rural residents and 0.5 d for residents of the cities of Gomel, Minsk, and Mogilev;
ε_j = is the fraction of daily fallout of ^{131}I on day j (Table 7);
$a_{k,j}$ = is the deposition density, relative to ^{131}I, of radionuclide k on day j;
η_{kj} = is the mass interception coefficient of plant for radionuclide k and day j, i.e., the fraction of radionuclide k initially retained by unit mass of leafy vegetable or of grass (Chamberlain 1970); it was taken to be 0.7 m^2 kg^{-1} (fresh weight) for iodine and tellurium for dry deposition, and 0.1 m^2 kg^{-1} for iodine and 0.2 m^2 kg^{-1} for tellurium for wet deposition;
λ_g = 0.15 d^{-1} is the effective removal rate of the stable nuclide from leafy vegetables;
λ_k = the radioactive decay constant of radionuclide k, d^{-1}; and
N = the day when consumption of contaminated food was terminated; it was taken to be 7 d (4 May 1986) for zone 1, 10 d (7 May 1986) for zone 2, and 60 d for all other zones.

Estimation of the time-integrated contamination of hands

A similar equation can be used to estimate the time-integrated contamination of hands:

$$IC_{hd,k} = k_h \times \sum_{j=0}^{N} \frac{\varepsilon_j \cdot a_{k,j} \cdot \eta_{k,j}}{\lambda_k} \times [1 - e^{-(\lambda_g + \lambda_k) \cdot (N-j)}], \quad (9)$$

where k_h is the fraction of activity transferred from the contaminated ground to the hands and then licked by a child. The value of k_h was taken to be 0.1, which is the upper bound of the estimates obtained for occupational exposures (Badyin et al. 1980).

Estimation of the time-integrated concentrations of radionuclides in fresh milk

The time-integrated concentrations of radionuclide k in fresh milk, $IC_{mk,k}$, were calculated according to the following equation, in which the fact that milk is consumed at discrete times after milking is taken into account:

$$IC_{mk,k} = \frac{1}{n} \times \sum_{t=0}^{N} \sum_{ij=1}^{n} [C_{mk,k}(t)]_{ij} \times e^{-\lambda_k \cdot \tau_{ij}}, \quad (10)$$

where:

n = 3 is the number of times milk was consumed in a day; it is assumed to be equal to the number of milkings per day;
t = the time of milk consumption after the accident, d;
N = the day when consumption of contaminated milk was terminated;
ij = an index reflecting the consumption of milk on day t [ij = 1 at 8 a.m.; ij = 2 at 2 p.m.; and ij =3 at 8 p.m. (Moscow times)];
$[C_{mk,k}(t)]_{ij}$ = is the normalized concentration of radionuclide k in the portion of milk, ij, consumed on day t, m^2 × L^{-1}; and
τ_{ij} = the delay from milking to consumption for the portion of milk ij, d. The values of τ_{ij} were taken to be 0 d for rural inhabitants and 0.5 d for people living in urban areas (cities of Gomel, Minsk, and Mogilev).

The concentration $[C_{mk,k}(t)]_{ij}$ was estimated on the basis of the following assumptions:

- a daily consumption of pasture grass by cow of 40 kg d^{-1} (fresh weight); however, the consumption of pasture grass is assumed to take place only during the day, from 8 a.m. to 8 p.m.;
- a yield of pasture grass of 0.24 kg m^{-2} (fresh weight) (Anonymous 1989);
- a daily consumption of soil by cow of 1 kg d^{-1};
- a mass of soil per unit area of ground in the layer that is consumed by cow of 1 kg m^{-2} (Simon et al. 1990);
- a feed-to-milk transfer coefficient of 6 × 10^{-3} d L^{-1} for stable iodine and of 5 × 10^{-4} d L^{-1} for stable tellurium (Garner 1967); and
- a biological clearance rate of 0.54 d^{-1} for stable iodine and 0.69 d^{-1} for stable tellurium.

Estimation of the relative intakes of the short-lived radionuclides via ingestion

Eqns (8) to (10) were used to calculate the estimated ratios, relative to the time-integrated concentrations of ^{131}I in cow's milk, $IC_{mk,1}$, of the time-integrated concentrations of short-lived radionuclides and ^{131}I in milk, $IC_{mk,k}/IC_{mk,1}$, and leafy vegetables, $IC_{lv,k}/IC_{mk,1}$, and of the time-integrated contamination of hands, $IC_{hd,k}/IC_{mk,1}$. The results are presented in Table 10 for the 10 zones of Belarus. As expected, most of the ratios for ^{132}Te, ^{132}I, and ^{133}I are lower than one, and the ratios for ^{131m}Te and ^{135}I are much lower than those for ^{132}Te, ^{132}I, and ^{133}I.

The ratios of the intakes from ingestion, relative to ^{131}I, $w_{p,k}$, were estimated according to eqn (7) using the time-integrated concentrations presented in Table 10 and the parameter values given in the previous paragraphs. The results are shown in Table 11.

Estimates of the contribution of the short-lived radionuclides to the thyroid dose

Estimates of the relative contribution of the short–lived radionuclides to the absorbed internal thyroid dose for the 10 zones of Belarus were derived from eqn (4) using the values presented in Tables 4, 8, 9, and 11. The results, according to age group and zone of residence, are presented in Table 12; they range from 0.003 for infants in zone 8 to 0.1 for teenagers in zone 1. Among the short-lived radionuclides, the most important contributors to the thyroid dose are ^{132}Te and ^{133}I in proportions that vary according to the zone and residence and to the age group that are considered.

ESTIMATES OF INDIVIDUAL THYROID DOSE: RESULTS AND DISCUSSION

For the 107 cases and the 214 controls, thyroid dose estimates resulting from the intake of ^{131}I have been

Table 10. Estimated ratios, relative to the time-integrated concentrations of ^{131}I in cow's milk, $IC_{mk,l}$, of the time-integrated concentrations of short-lived radionuclides and ^{131}I in milk, $IC_{mk,k}/IC_{mk,l}$, and leafy vegetables, $IC_{lv,k}/IC_{mk,l}$, and of the time-integrated contamination of hands, $IC_{hd,k}/IC_{mk,l}$.

Zone number	^{131m}Te	^{131}I	^{132}Te	^{132}I	^{133}I	^{135}I
			Ratios of time-integrated concentrations in milk			
1	$2.4\ 10^{-3}$	1.0	0.048	0.211	0.176	$9.4\ 10^{-3}$
2	$8.4\ 10^{-4}$	1.0	0.028	0.151	0.068	$1.3\ 10^{-3}$
3[a]	$1.7\ 10^{-3}$	1.0	0.073	0.382	0.028	$1.2\ 10^{-4}$
4	$8.3\ 10^{-5}$	1.0	0.006	0.006	0.011	$4.9\ 10^{-6}$
5[a]	$1.4\ 10^{-4}$	1.0	0.010	0.054	0.012	$5.7\ 10^{-5}$
6[a]	$1.1\ 10^{-4}$	1.0	0.009	0.011	0.008	$1.8\ 10^{-5}$
7	$3.7\ 10^{-4}$	1.0	0.016	0.085	0.030	$1.5\ 10^{-4}$
8[a]	$7.7\ 10^{-5}$	1.0	0.008	0.009	0.005	$7.2\ 10^{-6}$
9	$4.5\ 10^{-4}$	1.0	0.020	0.106	0.030	$2.9\ 10^{-4}$
10	$5.5\ 10^{-5}$	1.0	0.008	0.045	0.004	$1.1\ 10^{-4}$
			Leafy vegetables/^{131}I in milk			
1	0.120	3.21	1.88	1.93[b]	0.982	0.120
2	0.042	3.09	1.08	1.11[b]	0.378	0.017
3[a]	0.076	2.18	2.41	2.48[b]	0.124	$1.2\ 10^{-3}$
4	0.006	2.82	0.23	0.23[b]	0.093	$2.3\ 10^{-4}$
5[a]	0.006	2.36	0.34	0.35[b]	0.053	$6.3\ 10^{-4}$
6[a]	0.007	2.52	0.36	0.37[b]	0.055	$7.5\ 10^{-4}$
7	0.018	2.68	0.58	0.60[b]	0.167	$1.9\ 10^{-3}$
8[a]	0.005	2.64	0.33	0.34[b]	0.042	$3.2\ 10^{-4}$
9	0.022	2.68	0.73	0.75[b]	0.167	$3.7\ 10^{-3}$
10	0.003	2.67	0.29	0.30[b]	0.023	$1.4\ 10^{-3}$
			Contamination of hands/^{131}I in milk			
1	0.031	0.92	0.52	0.54[b]	0.252	0.029
2	0.011	0.91	0.31	0.31[b]	0.097	$4.1\ 10^{-3}$
3[a]	0.060	3.92	2.09	2.15[b]	0.189	$2.1\ 10^{-3}$
4	$1.4\ 10^{-3}$	1.15	0.07	0.07[b]	0.023	$5.0\ 10^{-5}$
5[a]	$4.8\ 10^{-3}$	2.90	0.24	0.24[b]	0.085	$6.5\ 10^{-4}$
6[a]	$5.2\ 10^{-3}$	3.11	0.25	0.26[b]	0.081	$7.2\ 10^{-4}$
7	$4.8\ 10^{-3}$	1.10	0.18	0.18[b]	0.043	$4.7\ 10^{-4}$
8[a]	$2.6\ 10^{-3}$	1.95	0.16	0.16[b]	0.030	$1.2\ 10^{-4}$
9	$5.9\ 10^{-3}$	1.10	0.22	0.23[b]	0.043	$9.1\ 10^{-4}$
10	$7.4\ 10^{-4}$	1.11	0.09	0.09[b]	0.006	$3.4\ 10^{-4}$

[a] Areas with substantial wet deposition.
[b] In radioactive equilibrium with ^{132}Te.

Table 11. Estimated ratios of the intakes from ingestion, relative to ^{131}I, $w_{p,k}$, for 6 age groups, for the 5 short-lived radionuclides and the 10 zones of Belarus.

Zone number	Age-group, y	^{131m}Te	^{132}Te	^{132}I	^{133}I	^{135}I
1	0–1	2.38×10^{-3}	0.048	0.215	0.175	9.37×10^{-3}
	1–2	5.60×10^{-3}	0.098	0.249	0.187	0.012
	3–7	7.47×10^{-3}	0.127	0.269	0.194	0.014
	8–12	8.52×10^{-3}	0.143	0.280	0.198	0.014
	13–17	8.52×10^{-3}	0.143	0.280	0.198	0.014
	Adult	7.07×10^{-3}	0.121	0.265	0.192	0.0132
2	0–1	8.41×10^{-4}	0.028	0.151	0.067	1.27×10^{-3}
	1–2	1.98×10^{-3}	0.057	0.169	0.072	1.63×10^{-3}
	3–7	2.65×10^{-3}	0.074	0.179	0.075	1.84×10^{-3}
	8–12	3.02×10^{-3}	0.083	0.185	0.076	1.96×10^{-3}
	13–17	3.02×10^{-3}	0.084	0.185	0.076	1.95×10^{-3}
	Adult	2.50×10^{-3}	0.070	0.177	0.074	1.79×10^{-3}
3[a]	0–1	1.69×10^{-3}	0.073	0.382	0.027	1.13×10^{-4}
	1–2	4.07×10^{-3}	0.148	0.430	0.029	1.48×10^{-4}
	3–7	5.50×10^{-3}	0.194	0.458	0.030	1.71×10^{-4}
	8–12	6.32×10^{-3}	0.219	0.474	0.031	1.85×10^{-4}
	13–17	6.45×10^{-3}	0.224	0.473	0.031	1.91×10^{-4}
	Adult	5.38×10^{-3}	0.191	0.452	0.030	1.75×10^{-4}
4	0–1	8.29×10^{-5}	0.006	0.007	0.012	4.86×10^{-6}
	1–2	2.34×10^{-4}	0.012	0.013	0.014	1.09×10^{-5}
	3–7	3.24×10^{-4}	0.016	0.016	0.015	1.45×10^{-5}
	8–12	3.74×10^{-4}	0.018	0.018	0.015	1.65×10^{-5}
	13–17	3.73×10^{-4}	0.018	0.018	0.015	1.64×10^{-5}
	Adult	3.03×10^{-4}	0.015	0.016	0.014	1.36×10^{-5}
5[a]	0–1	1.40×10^{-4}	0.010	0.055	0.011	5.73×10^{-5}
	1–2	3.38×10^{-4}	0.020	0.061	0.012	7.49×10^{-5}
	3–7	4.58×10^{-4}	0.026	0.065	0.013	8.58×10^{-5}
	8–12	5.17×10^{-4}	0.030	0.031	0.010	6.01×10^{-5}
	13–17	5.42×10^{-4}	0.031	0.067	0.013	9.38×10^{-5}
	Adult	4.51×10^{-4}	0.026	0.064	0.013	8.57×10^{-5}
6[a]	0–1	1.11×10^{-4}	0.009	0.011	0.008	1.70×10^{-5}
	1–2	3.19×10^{-4}	0.020	0.022	0.009	3.89×10^{-5}
	3–7	4.45×10^{-4}	0.027	0.028	0.010	5.23×10^{-5}
	8–12	5.27×10^{-4}	0.030	0.067	0.013	9.21×10^{-5}
	13–17	5.32×10^{-4}	0.031	0.032	0.011	6.24×10^{-5}
	Adult	4.38×10^{-4}	0.026	0.027	0.010	5.25×10^{-5}
7	0–1	3.65×10^{-4}	0.016	0.085	0.0301	1.49×10^{-4}
	1–2	8.66×10^{-4}	0.032	0.095	0.033	1.93×10^{-4}
	3–7	1.16×10^{-3}	0.041	0.101	0.034	2.19×10^{-4}
	8–12	1.33×10^{-3}	0.047	0.105	0.035	2.33×10^{-4}
	13–17	1.33×10^{-3}	0.047	0.105	0.035	2.33×10^{-4}
	Adult	1.10×10^{-3}	0.039	0.100	0.034	2.12×10^{-4}
8[a]	0–1	7.62×10^{-5}	0.008	0.010	0.005	7.14×10^{-6}
	1–2	2.17×10^{-4}	0.018	0.019	0.006	1.61×10^{-5}
	3–7	3.02×10^{-4}	0.023	0.024	0.007	2.13×10^{-5}
	8–12	3.50×10^{-4}	0.026	0.028	0.007	2.43×10^{-5}
	13–17	3.56×10^{-4}	0.027	0.028	0.007	2.43×10^{-5}
	Adult	2.91×10^{-4}	0.022	0.024	0.007	2.03×10^{-5}
9	0–1	4.44×10^{-4}	0.020	0.106	0.030	2.88×10^{-4}
	1–2	1.05×10^{-3}	0.040	0.119	0.033	3.74×10^{-4}
	3–7	1.41×10^{-3}	0.052	0.127	0.034	4.24×10^{-4}
	8–12	1.62×10^{-3}	0.058	0.131	0.035	4.52×10^{-4}
	13–17	1.61×10^{-3}	0.059	0.131	0.035	4.51×10^{-4}
	Adult	1.33×10^{-3}	0.049	0.125	0.034	4.11×10^{-4}
10	0–1	5.45×10^{-5}	0.008	0.045	0.004	1.06×10^{-4}
	1–2	1.29×10^{-4}	0.016	0.050	0.004	1.38×10^{-4}
	3–7	1.74×10^{-4}	0.021	0.053	0.005	1.56×10^{-4}
	8–12	1.98×10^{-4}	0.023	0.055	0.005	1.67×10^{-4}
	13–17	1.98×10^{-4}	0.023	0.055	0.005	1.66×10^{-4}
	Adult	1.64×10^{-4}	0.020	0.052	0.005	1.52×10^{-4}

[a] Wet deposition areas.

assessed and used in the case-control study of thyroid cancer (Astakhova et al. 1998). Thyroid doses resulting from the intake of short-lived radioiodines and radiotelluriums also have been estimated.

Thyroid doses resulting from the intake of ^{131}I

The distribution, according to zone of residence at the time of the accident, of the estimated ^{131}I thyroid doses for the cases and the controls obtained by means of

Table 12. Estimates of the relative contribution of short-lived radionuclides to internal absorbed thyroid dose of inhabitants for considered locations (expressed as ratios of ^{131}I thyroid dose).

Zone number	Relative fraction according to age group, y					
	0–1	1–2	3–7	8–12	13–17	adult
1	0.0676	0.0672	0.0851	0.0972	0.0995	0.0821
2	0.0284	0.0282	0.0356	0.0404	0.0413	0.0342
3[a]	0.0256	0.0255	0.0307	0.0334	0.0335	0.0282
4	0.0060	0.0065	0.0121	0.0170	0.0256	0.0348
5[a]	0.0060	0.0061	0.0077	0.0088	0.0090	0.0073
6[a]	0.0053	0.0059	0.0107	0.0152	0.0223	0.0295
7	0.0137	0.0137	0.0175	0.0201	0.0205	0.0168
8[a]	0.0030	0.0032	0.0040	0.0042	0.0048	0.0050
9	0.0149	0.0149	0.0193	0.0224	0.0228	0.0186
10	0.0036	0.0036	0.0050	0.0060	0.0061	0.0049

[a] Areas with substantial wet deposition.

the "inferred" methodology and used in the case-control study is presented in Table 13. As expected, the highest thyroid doses were found in the southern part of Gomel Region (zones 1 and 2) and in the Gomel-Mogilev Spot (zone 3), while the lowest values were estimated in Vitebsk Region (zone 10) and in the western part of the country (zone 9). The median thyroid doses are approximately 0.2 Gy for the cases and 0.07 Gy for the controls. The range of the thyroid doses extends from 0.00002 to 4.3 Gy.

The overall thyroid dose distributions for the 107 cases and for the 214 controls are presented in Fig. 3. The dose estimates for the controls are, on average, somewhat lower than those found for the cases.

Comparison of dose estimates obtained with the three methods. The ^{131}I thyroid dose estimates that are used in the case-control study are those derived from the "inferred" methodology as it was available for all cases and controls. However, for a number of cases and controls, "measured" and "passport" doses could also be estimated and compared with the "inferred" doses. The comparison between the "inferred" doses and (1) the "measured" doses for the 12 cases with direct thyroid measurements, (2) the "passport" doses available for 51 cases, and (3) the "passport" doses available for 58 controls are shown in Figs. 4a, 4b, and 4c, respectively. A good agreement is obtained for all cases when the 95% confidence intervals are taken into consideration.

On the whole, therefore, the three methods of thyroid dose estimation yielded similar results when direct comparisons were possible. This gives some degree of confidence in the magnitude of the error bars assigned to the estimates obtained with the "inferred" dose methodology. However, it should be kept in mind that the three methods are based on the use of the direct thyroid measurements and that they are not completely independent. The estimation of "inferred" doses for subjects living in areas without direct thyroid measurements is associated with high uncertainties, and the results cannot be compared with those obtained using the other two methods. The areas without direct thyroid measurements are mainly found in the western and

Table 13. Distribution of the estimated ^{131}I thyroid doses for the cases and the controls according to zone of residence at the time of the accident.

Zone number	Cases		Controls	
	Median (range), Gy	Number	Median (range), Gy	Number
1	2.4 (0.71–4.3)	5	—	0
2	0.63 (0.11–2.2)	27	0.30 (0.071–2.9)	21
3[a]	0.60 (0.11–3.1)	17	0.40 (0.00002[b]–1.5)	27
4	0.20 (0.12–0.57)	19	0.27 (0.12–0.57)	13
5[a]	0.15 (0.015–0.37)	9	0.069 (0.0072–0.38)	60
6[a]	—	0	0.079 (0.053–0.19)	9
7	0.038 (0.02–0.23)	10	0.099 (0.021–0.55)	16
8[a]	0.025 (0.023–0.04)	5	0.038 (0.022–0.10)	20
9	0.012 (0.0062–0.079)	13	0.01 (0.0029–0.29)	44
10	0.0068 (0.0061–0.0074)	2	0.0034 (0.0024–0.0081)	4
All country	0.22 (0.0061–4.3)	107	0.071 (0.001–2.9)	214

[a] Areas with substantial wet deposition.
[b] The lowest dose, estimated for a subject who was exposed in utero.

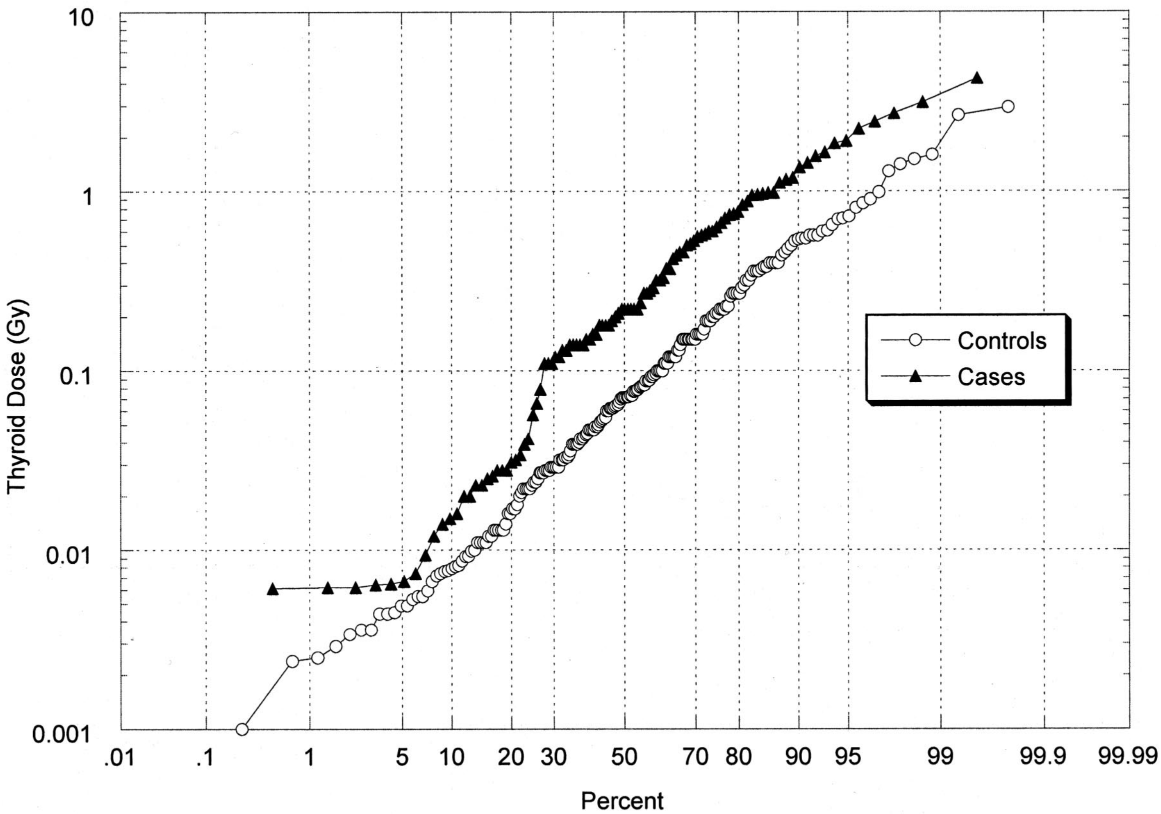

Fig. 3. Overall thyroid dose distributions for the 107 cases and for the 214 controls.

northern parts of Belarus. The main additional sources of uncertainty related to the use of the "inferred" dose methodology in areas without direct thyroid measurements are thought to arise from differences in (1) the ratio of ^{131}I and ^{137}Cs activities in soil, which depends on the date and type of deposition and can be different in the northern and western parts of Belarus from the values found in southern Belarus; (2) the beginning of the grazing season, which occurs earlier in southern Belarus than in the northern territories; and (3) the origin of consumed milk, especially in urban areas. In order to reduce uncertainties related to the estimation of ^{131}I deposition density, use could be made of ^{129}I measurements in soil (Straume et al. 1996).

Thyroid doses resulting from the intake of short-lived radioiodines ^{132}I, ^{133}I, and ^{135}I and radiotelluriums ^{131m}Te and ^{132}Te.

In the epidemiological study (Astakhova et al. 1998), only the contribution to the thyroid dose resulting from the intake of ^{131}I was taken into consideration, as the other components of the thyroid dose, and, in particular, the thyroid dose from internal irradiation due to the intake of short-lived radioiodines (^{132}I, ^{132}I, and ^{135}I) and radiotelluriums (^{131m}Te and ^{132}Te) were considered to be small on the basis of a cursory analysis. In this paper, the thyroid dose from radioiodines and radiotelluriums have been estimated in detail.

The distribution of the estimated thyroid doses resulting from the intake of short-lived radioiodines and radiotelluriums for the cases and the controls is presented in Table 14 according to zone of residence at the time of the accident. As in the case of the thyroid doses resulting from the intake of ^{131}I, the highest thyroid doses were found in the southern part of Gomel Region (zones 1 and 2) and in Gomel-Mogilev Spot (zone 3), while the lowest values were estimated in Vitebsk Region (zone 10) and in the western part of the country (zone 9). The median thyroid doses from short-lived radionuclides are approximately 0.003 Gy for the cases and 0.0009 Gy for the controls. The range of the thyroid doses resulting from the intake of short-lived radioiodines and radiotelluriums extends from 8×10^{-9} Gy to 0.4 Gy.

As shown in Table 12, the ratios of the estimated thyroid doses from the short-lived radioiodines and radiotelluriums and from ^{131}I vary according to zone of residence and to age at the time of the accident. The range of the ratios is from 0.003 to 0.1. The highest values are found in zones 1 and 2, which are the closest to the reactor, and in zone 3, where deposition occurred soon after the accident. The lowest values are observed in

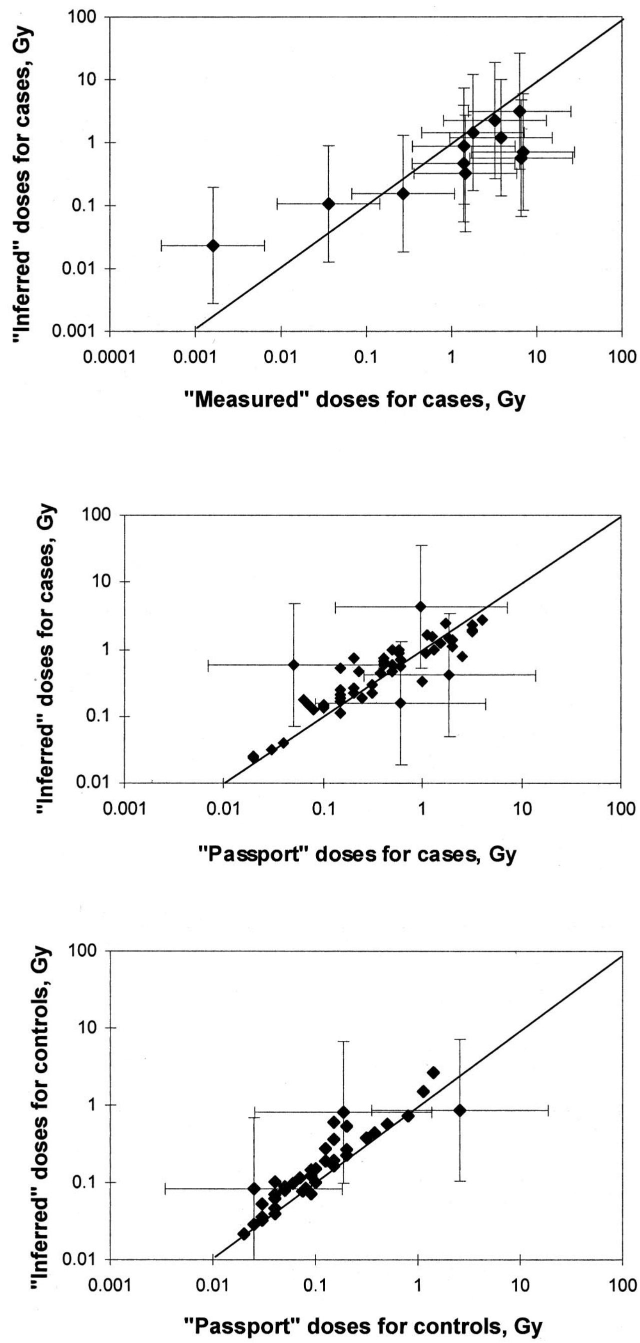

Fig. 4. Comparison of the "inferred" thyroid dose estimates and (a) the "measured" thyroid dose estimates for the 12 cases with direct thyroid measurements, (b) the "passport" thyroid dose estimates available for 51 cases, and (c) the "passport" thyroid dose estimates available for 58 controls. The error bars represent 95% confidence intervals.

zone 8 (Minsk city) and in zone 10 (Vitebsk Region), which are far from the reactor, thus giving more time for the short-lived radionuclides to decay before deposition occurred. The median values of the ratios are approximately 0.02 for both cases and controls.

SUMMARY

Within the framework of a case-control study related to the incidence of thyroid cancer among Belarusian children following the Chernobyl accident, thyroid dose estimates have been assessed for 107 cases and 214 controls (Astakhova et al. 1998). Although only the contribution to the thyroid dose resulting from the intake of ^{131}I was taken into consideration in the epidemiological study, three additional components of the thyroid dose have been estimated as well: (1) the thyroid dose from internal irradiation due to the intake of short-lived radioiodines (^{132}I, ^{132}I, and ^{135}I) and radiotelluriums (^{131m}Te and ^{132}Te); (2) the thyroid dose from internal irradiation due to other radionuclides, such as ^{134}Cs and ^{137}Cs, incorporated in the body; and (3) the thyroid dose from external irradiation due to radionuclides deposited on the ground. The manner in which the thyroid doses resulting from the intake of ^{131}I and from the intake of short-lived radioiodines (^{132}I, ^{132}I, and ^{135}I) and radiotelluriums (^{131m}Te and ^{132}Te) have been estimated for the cases and the controls is described in this paper. The contributions to the thyroid doses arising from external irradiation and from internal irradiation from radionuclides deposited in organs other than the thyroid will be discussed in a companion paper.[§§]

Several methods of thyroid dose reconstruction have been used in Belarus (Gavrilin et al. 1999; Drozdovitch et al. 1997) to estimate the thyroid doses resulting from the intake of ^{131}I. All of the methods are based on the information derived from the direct thyroid measurements that were made in the most contaminated areas of Belarus soon after the accident. The choice of the method depends on the available information for all subjects. In this case-control study, only the place of residence of the subjects within a few weeks after the accident and the ^{137}Cs deposition density at those locations was available for all subjects. The dosimetry method that was selected makes use of the observed relationships between the ^{137}Cs deposition density and the mean adult thyroid doses derived for the people with direct thyroid measurements in the areas considered (Gavrilin et al. 1999). This method provides dose estimates that are more uncertain than those obtained with methods that make use of more extensive information on the subjects or on environmental radiation, but those other methods are not applicable to all subjects. The median thyroid doses are found to be approximately 0.2 Gy for the cases and 0.07 Gy for the controls. The range of thyroid doses extends from 0.00002 to 4.3 Gy. As expected, the highest thyroid doses were found in the southern part of Gomel Region and in Gomel-Mogilev Spot where the highest deposition densities of ^{137}Cs have been observed, while the lowest

Table 14. Distribution of the estimated thyroid doses from the short-lived radioiodines (^{132}I, ^{133}I, and ^{135}I) and radiotelluriums (^{131m}Te and ^{132}Te) for the cases and the controls according to zone of residence at the time of the accident.

Zone number	Cases		Controls	
	Median (range), Gy	Number	Median (range), Gy	Number
1	0.21 (0.067–0.38)	5	—	0
2	0.023 (0.0038–0.063)	27	0.011 (0.0028–0.10)	21
3[a]	0.019 (0.0031–0.080)	17	0.011 ($8\ 10^{-9}$[b]–0.041)	27
4	0.0024 (0.0021–0.014)	19	0.0025 (0.0021–0.0034)	13
5[a]	0.0019 (0.00014–0.0099)	9	0.00086 (0.000059–0.0093)	60
6[a]	—	0	0.00093 (0.0008–0.0011)	9
7	0.00061 (0.00039–0.0042)	10	0.0016 (0.00042–0.0082)	16
8[a]	0.00010 (0.000097–0.00015)	5	0.00015 (0.000091–0.00030)	20
9	0.00021 (0.00011–0.0014)	13	0.00018 (0.000063–0.0050)	44
10	0.000027 (0.000026–0.000028)	2	0.000017 (0.000014–0.000029)	4
All country	0.0031 (0.000026–0.38)	107	0.00093 ($8\ 10^{-9}$–0.10)	214

[a] Areas with substantial wet deposition.
[b] The lowest dose, estimated for a subject who was exposed in utero.

values were estimated in Vitebsk Region and in the western part of the country, which are the least contaminated areas of the country. For a limited number of subjects, the thyroid doses could be estimated by means of one or two more accurate methods; a comparison of the results obtained shows a good agreement.

The thyroid doses resulting from the intake of short-lived radioiodines (^{132}I, ^{132}I, and ^{135}I) and radiotelluriums (^{131m}Te and ^{132}Te) have been estimated for the cases and the controls on the basis of limited information: (1) the operational history of the reactor during the 24 h preceding the accident; and (2) a few measurements of deposition density of ^{133}I and ^{132}Te. The territory of Belarus was divided into 10 zones where environmental conditions were assumed to be uniform and the thyroid doses from short-lived radionuclides have been scaled to those corresponding to the intake of ^{131}I. The median thyroid doses from short-lived radionuclides are found to be approximately 0.003 Gy for the cases and 0.0009 Gy for the controls. The range of the thyroid doses resulting from the intake of short-lived radioiodines and radiotelluriums extends from 8×10^{-9} to 0.4 Gy. As in the case of the thyroid doses resulting from the intake of ^{131}I, the highest thyroid doses were found in the southern part of the Gomel Region (zones 1 and 2) and in the Gomel-Mogilev Spot (zone 3), while the lowest values were estimated in Vitebsk Region (zone 10) and in the western part of the country (zone 9). The ratios of the estimated thyroid doses from the short-lived radioiodines and radiotelluriums and from ^{131}I for the cases and the controls range from approximately 0.003 to 0.1, with median values of approximately 0.02 for both cases and controls.

The contributions to the thyroid doses arising from external irradiation and from internal irradiation from radionuclides deposited in organs other than the thyroid will be discussed in a companion paper.[§§] They are also found to be small in comparison to the thyroid doses resulting from the intake of ^{131}I.

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